SYSTEM AND METHOD FOR CONTROLLING THE TEMPERATURE AND INFRARED SIGNATURE OF AN ENGINE

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

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BACKGROUND OF THE INVENTION

1) Field of the Invention

[0002] The present invention relates to the control of temperature in an engine and, more particularly, to the use of fuel for cooling engine components and especially an exhaust nozzle such as in an aircraft engine.

2) Description of Related Art

[0003] Infrared emissions from aircraft, ships, tanks, other vehicles and structures, and the like provide an "infrared signature" that generally increases as the temperature of the components and exhausts of those devices increase. For example, the exhaust nozzle of a turbine engine of an aircraft receives the hot exhaust gases from the engine and can operate at temperatures in excess of 1000 °F. Thus, the nozzle can emit significant infrared energy, thereby contributing to the overall infrared signature of the aircraft. Excessive infrared emissions, e.g., as emitted from a hot nozzle, can make the aircraft more easily detectable to infrared detection equipment, which can also use the infrared signature to identify the aircraft.

[0004] Some conventional turbine engines include an annular bypass duct, or fan duct, that surrounds the engine. A fan blows air into the bypass duct, the air flows through the duct along the length of the engine, and the air is then mixed with the exhaust gas in the nozzle. Thus, the air shrouds the high temperature combustion process within the engine and also cools the nozzle, thereby reducing the infrared signature of the aircraft. The maximum temperature of the air in the bypass duct is affected by various operating parameters including the ambient temperature of the air entering the duct, the operating temperature of the engine, the amount of air circulated through the duct, and the like. Typically, the air in the bypass duct reaches a

temperature of between about 500 °F and 600 °F, thereby limiting the cooling effect of the air on the engine components, especially near the nozzle, and limiting the reducing effect of the air on the aircraft's infrared signature.

[0005] Thus, there exists a need for an engine system and method for controlling the temperature of the components of the engine, such as the nozzle, and/or other components on aircraft and other vehicles and devices. Preferably, the system should be capable of cooling the components directly or by cooling a flow of air that is used for cooling.

BRIEF SUMMARY OF THE INVENTION

[0006] The present invention provides a system and method for cooling at least a portion of an engine and controlling the infrared signature of the engine. According to one present invention, the fuel used for combustion in the engine is also used to cool one or more hot components in the engine. For example, the fuel may be utilized to cool the exhaust nozzle and thus reduce the infrared signature of the engine.

[0007] According to one embodiment of the present invention, the system includes an engine passage that extends between an inlet end and an exhaust end. The passage is structured to receive at least one gas therethrough, such as exhaust gas in a central passage and air through a fan duct. Fuel is supplied to a combustion device in the passage for combustion therein. A nozzle at the exhaust end of the engine passage receives the gas from the engine passage and discharges the gas. Further, a heat exchanger is configured to receive a flow of the fuel before the fuel is combusted and a flow of a fluid, e.g., air. The heat exchanger transfers thermal energy from the fluid to the fuel to cool the fluid and delivers the cooled fluid to the nozzle. In some cases, the fuel can be heated to temperatures higher than 300 °F in the heat exchanger.

[0008] In one aspect of the invention, the heat exchanger is disposed in the engine passage and cools the air in the fan duct. For example, the heat exchanger can be disposed in the fan duct and configured to receive air passing therethrough and transfer thermal energy from the air to the fuel. The heat exchanger can be disposed in the duct at a position that is proximate longitudinally to an augmentor that discharges fuel into the central passage for combustion. Alternatively, the heat exchanger can be disposed in the central passage and configured to receive fuel and cool the exhaust nozzle and/or the augmentor. The heat exchanger can also

selectively function as an augmentor by discharging the fuel into the central passage for combustion.

[0009] According to another aspect of the present invention, the heat exchanger is disposed outside the engine passage and configured to receive a flow of air, transfer thermal energy from the air to the fuel, and deliver the cooled air to the engine passage. For example, the heat exchanger can receive the air from a compressor of a turbocooler. The air flows from the heat exchanger to a turbine of the turbocooler, where the air is expanded and further cooled before being delivered to the engine passage. The air flowing to the compressor of the turbocooler can be bleed air from a compressor in the engine passage. A precooler heat exchanger can also be provided for transferring thermal energy from the air flowing from the compressor in the engine passage to the fuel.

[0010] According to one method of the present invention, fuel and air are combusted in an engine passage to form an exhaust gas that is discharged from the engine passage. A flow of the fuel is circulated through a heat exchanger in the engine passage, and the fuel is delivered from the heat exchanger to the combustion device for combustion. The heat exchanger thermally communicates with the air and transfers thermal energy therefrom to the fuel to thereby cool the air that can then be used to cool the nozzle. For example, the fuel can circulate through a heat exchanger in the fan duct of the engine passage to cool a flow of air therethrough. Alternatively, the fuel can circulate through the augmentor in the central passage such that the augmentor transfers thermal energy to the fuel. In either case, the fuel can additionally circulate through a precooler heat exchanger that receives a flow of compressed air from a compressor in the engine passage such that the precooler heat exchanger transfers thermal energy from the air to the fuel.

[0011] According to another method, the fuel is circulated through a heat exchanger disposed outside the engine passage, and a flow of air is circulated through the heat exchanger to transfer thermal energy from the air to the fuel before the fuel is combusted. The cooled air is then delivered to the engine passage to cool hot engine components. For example, the flow of air passing through the heat exchanger can be compressed in a compressor of a turbocooler before the air is cooled in the heat exchanger. After being cooled in the heat exchanger, the air can be expanded and further cooled in a turbine of the turbocooler, then delivered to the engine passage.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0012] Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

[0013] Figure 1 is a schematic view illustrating a turbine engine with a fan duct heat exchanger according to one embodiment of the present invention;

[0014] Figure 2 is a schematic view illustrating a turbine engine with an air cooling device located outside the engine housing according to another embodiment of the present invention;

[0015] Figure 3 is a schematic view illustrating a turbine engine with an augmentor configured to circulate fuel for cooling according to yet another embodiment of the present invention;

[0016] Figure 4 is a schematic view illustrating a core portion of a heat exchanger with an electron tunneling device according to one embodiment of the present invention; and

[0017] Figure 5 is a schematic view illustrating a portion of the electron tunneling device of Figure 4.

DETAILED DESCRIPTION OF THE INVENTION

[0018] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

[0019] Referring now to the figures and in particular to Figure 1, there is shown a turbine engine **10** according to one embodiment of the present invention. While the engine **10** is described herein primarily as a thrust generation device for an aircraft, it is understood that the engine can alternatively be used for other applications such as for powering other vehicles. The engine **10** includes a housing **12** extending from an inlet side **14** to an outlet side **16** and defining an engine passage therebetween. More particularly, the engine passage includes a central passage **30** and an annular fan duct **32** or bypass duct that surrounds the central passage **30**. As is known in the field of turbine engines, the engine **10** includes a compressor **20** and turbine **22** mounted

axially on a shaft **24** in the central passage **30**. A combustor device **26** is configured to combust fuel and thereby drive the turbine **22** and compressor **20**. A fan **28** is also provided for directing air through the engine **10**. In particular, the air is directed through the central passage **30** of the engine **10** for combustion, i.e., along a main stream path of the engine **10**, and also through the fan duct **32**.

[0020] During operation of the engine, the compressor **20** is actuated by the shaft **24** to compress air, which is then combusted with fuel introduced into the engine **10** through the combustor **26**. The combustion of the fuel and air produces an expanded exhaust gas that flows in direction **34** through the central passage of the engine toward an exhaust nozzle **36**, from which the exhaust gas is discharged. As the exhaust gas expands and flows through the turbine **22**, the turbine **22** is rotated, thereby rotating the shaft **24** and actuating the compressor **20** and the fan **28**. An augmentor **38** can also be provided in the central passage **30** to deliver additional fuel to the stream of exhaust gas for further combustion. The expansion and resulting flow of the exhaust gas through the nozzle **36** provides thrust for the aircraft. In addition, a power transmission device such as a gear box **40** can be connected to the shaft **24** by a mechanical coupling **42** and thereby driven by the rotation of the shaft **24** during operation. Rotational energy transmitted through the gear box **40** can be used to power onboard devices such as fuel pumps, electrical generators, compressors, or the like. It will be appreciated that various alternative engine configurations, some including additional engine components, can be provided in keeping with the present invention.

[0021] Cooling of the engine **10** can be achieved using the air blown through the fan duct **32** by the fan **28**. The air enters the fan duct **32** at the inlet side **14** and flows in a direction **44** generally parallel to the flow of the exhaust gas in the central passage **30**. The air is cooler than the hot exhaust gas produced in the engine **10** and thus cools the outer surface of the engine **10**. Apertures **46** connect the fan duct **32** to the central passage **30** of the engine **10** at a location downstream of the turbine **22** so that a portion of the air from the fan duct **32** flows inward as indicated by direction **48** and mixes with the exhaust gas in the central passage **30**. The remaining portion of the air in the fan duct **32** is discharged through the nozzle **36**, e.g., through additional apertures **50** that are directed generally radially inward so that the air enters the central passage **30** in direction **52** at the nozzle **36**. Thus, the air is mixed with the hot exhaust gas and lowers the average temperature of the nozzle **36**. The cooling of the

engine components can decrease the infrared signature of the engine **10** and the aircraft, thereby reducing the detectability of the aircraft by infrared detection equipment. Further, the lower operating temperature of the engine components can reduce thermal stresses and extend the useful life of the engine components.

[0022] The cooling effect of the air can be enhanced with a fan duct heat exchanger **60** provided in the fan duct **32**. That is, the fan duct heat exchanger **60** can be positioned in the fan duct **32** and supported by a structure, such as a conventional portion of the structure of the engine **10**. The fan duct heat exchanger **60** receives engine fuel and transfers heat from the air in the duct **32** to the fuel. The fan duct heat exchanger **60** can be a generally annular device that extends around the central passage **30**. Typically, the heat exchanger **60** is positioned at an axial location in proximity to the augmentor **38** or downstream of the augmentor **38**. The fan duct heat exchanger **60** defines an inlet **62**, an outlet **64**, and at least one fluid circuit **66** therebetween for circulating the fuel in the fan duct **32**. The fluid circuit **66**, illustrated schematically in Figure 1, can be structured in various configurations. The fluid circuit **66** is configured to thermally communicate with the air in the fan duct **32**, i.e., by convection as the air flows around the fluid circuit **66**. For example, the heat exchanger **60** can be an air-to-liquid, cross-flow heat transfer device with fins to enhance the heat transfer. That is, the fuel can flow through a finned tube bundle and the air can flow outside the tubes, across the fins. A variety of other types and configurations of heat exchangers can alternatively be used. In some cases, the heat exchanger **60** can be an integral part of the fan duct **32**.

[0023] The fuel provided for cooling the fan duct heat exchanger **60** is the same fuel used for combustion in the operation of the engine **10**. The fuel is provided from a fuel source **70**, which is typically a tank or other vessel. In some embodiments, the fuel source **70** can include multiple vessels, e.g., multiple fuel tanks in various locations of the aircraft. Flow of the fuel to and from the source **70** is controlled by one or more pumps and control valves, shown as a single fuel flow control unit **72** in Figure 1. One or more pumps and/or valves or other control devices can also be provided separately and at various locations throughout the flow path of the fuel. In either case, a coupling **43** extending from the gear box **40** can be provided for actuating the pump(s). The control unit **72** can be configured to deliver the fuel through a supply line **74** in fluid communication with the fan duct heat exchanger **60**, which transfers thermal energy to the fuel from the air in the fan duct **32**. In addition,

the control unit **72** can deliver the fuel to one or more additional heat exchanging devices **76**, which transfer thermal energy to the fuel from air, oil, other fluids, or devices of the aircraft. The fuel can be delivered to the various heat exchanging devices **60**, **76** in series or parallel flows and the flow path of the fuel can be changed using bypass lines circumventing any of the devices and/or valves **78** configured to adjust the flow through particular lines.

[0024] After the fuel is heated in any of the heat exchangers **60**, **76**, the fuel can then be delivered as needed through lines **80**, **82** that provide fuel to a precooler heat exchanger **90** and the combustor **26**. A portion of the heated fuel can also be recirculated to the control unit **72**, e.g., through return line **84**. An air/fuel heat exchanger **86** can be provided for cooling fuel in or returning to the fuel source **70**. The air/fuel heat exchanger **86** circulates the fuel in communication with a flow of ram air, generally indicated by direction **88**, that cools the fuel. Thus, thermal energy transferred to the fuel in the heat exchangers **60**, **76** can be vented to the atmosphere or retained in the fuel until the fuel is circulated to the engine for combustion therein. The precooler heat exchanger **90**, which is configured to deliver the fuel to the combustor **26** for combustion in the engine **10**, is also be structured to receive a flow of bleed air from the compressor **20** through line **92**, and a valve **94** is provided for controlling the flow of the bleed air. The bleed air is cooled in the precooler heat exchanger **90**, i.e., by transferring thermal energy to the fuel flowing through the precooler heat exchanger **90** to the combustor **26**, and the bleed air can be used as a source of compressed air and/or as a cooling fluid in other onboard devices **96** throughout the aircraft such as a turbocooler or the like. The flow rate of the bleed air can be determined according to the cooling requirements of the onboard devices **96**, and the flow rate, in some cases, can be about the same as the flow rate of bleed air of conventional engines.

[0025] The engine **10** of Figure 1 can be operated in various modes of operation. For example, in one mode of operation, the fuel is circulated through the heat exchanging device **76**, e.g., to cool engine oil or components, through the fan duct heat exchanger **60** to cool the air in the fan duct **32**, and then through the precooler heat exchanger **90** to cool bleed air from the compressor **20** before being delivered to the combustor **26** for combustion in the engine **10**. Thus, the fuel is heated in a three-stage process, first cooling a fluid in the heat exchanging device **76**, then in the fan duct heat exchanger **60**, and finally in the precooler heat exchanger **90**.

Alternatively, the fuel can be circulated to fewer or none of the heat exchanging devices **60**, **76**, **90** before being combusted, or some of the fuel can be used to cool one or more of the devices **60**, **76**, **90** and then returned to the control unit **72** and/or the fuel source **70** before being combusted in the engine **10**. Fuel for combustion in the engine **10** can be provided to the combustor **26** and/or to the augmentor **38**, i.e., through line **98**. In any case, the pumps, valves, and other control devices that are inside or outside the control unit **72** can be controlled according to the operational mode of the engine **10** so that the fuel is used to achieve a desired rate of cooling in the various components of the engine **10**. For example, the flow of fuel to the fan duct heat exchanger **60** can be adjusted according to the temperature of the fuel and the air in the fuel duct **32**, the temperature of the nozzle **36** or other engine components, the speed or other operational characteristics of the engine **10**, and the like. Some or all of the control devices in the engine **10**, can be controlled by one or more electronic controllers.

[0026] In addition, the operation of the engine **10** can be controlled according to the type of fuel used so that a temperature limit of the fuel is not exceeded as the fuel is heated. Conventional jet fuel such as JP-8 is stable only up to a temperature of about 300 °F, and therefore cannot generally be used for cooling hot gases such as the fan air, which is typically in the temperature range of 500 °F and 600 °F. However, certain fuels can include additives to increase the temperature at which the fuels become unstable. Such fuels, generally referred to as high heat sink fuels, can be stable to temperatures greater than conventional jet fuels. For example, JP-8+225 fuel is stable to a temperature of about 525 °F. Thus, where JP-8+225 fuel or another high heat sink fuel is used, the fan duct heat exchanger **60** can be used to transfer sufficient thermal energy from the air in the fan duct **32** to lower the temperature of the air, e.g., by about 50 °F to 200 °F while heating the fuel to a temperature as high as about 525 °F. The reduction in the temperature of the air can cool the nozzle **36**, e.g., so that the nozzle **36** is nearly 50 °F to 200 °F cooler than the nozzle **36** would otherwise be if the air in the fan duct **32** were not cooled by the fuel. The heated fuel from the outlet **64** of the fan duct heat exchanger **60** can be circulated through lines **82** and **80** to the precooler heat exchanger **90** and then to the combustor **26** for combustion in the engine **10** as needed for operation.

[0027] For example, in one embodiment of the present invention, the air flows through the heat exchanger **60** with at a rate of about 2000 lbm/min. If the air enters

the heat exchanger at a temperature of about 514 °F and is cooled by the fuel to a temperature of about 420 °F, the rate of thermal transfer to the fuel is equal to about 45,120 Btu/min, and is expected to result in a reduction in the infrared signature of the nozzle **36** of about 15%. If the air flows to the heat exchanger with the same flow rate and temperature but is cooled to 448 °F by the fuel in the heat exchanger, the rate of thermal transfer to the fuel is equal to about 31,680 Btu/min, which is expected to result in a reduction in the infrared signature of the nozzle **36** of about 11%. In other embodiments of the present invention, the flow rates, temperatures, and thermal transfer rates can be different, thereby potentially changing the temperature and infrared signature of the nozzle **36**. For example, in one embodiment, the flow rate of the air through the heat exchanger **60** is between about 125 lbm/min and 5500 lbm/min, and the flow rate of the fuel through the heat exchanger **60** is between about 50 lbm/min and 550 lbm/min, though the flow rates can be greater or lesser in other embodiments of the invention.

[0028] While the fan duct heat exchanger **60** described above can be used to cool the air in the fan duct **32**, in other embodiments of the present invention the engine **10** can additionally or alternatively include a cooling device located outside the engine housing **12**. For example, as shown in Figure 2, a turbocooler **100** and heat exchanger **110** are provided external to the engine housing **12** and configured to provide a flow of cool air to the fan duct **32**. In the embodiment of Figure 2, the fan **28** is configured to blow air into the inlet side **14** of the fan duct **32**. The fan duct **32** is structured to direct a first portion of the air into the central passage **30**, as indicated by direction **48a**, and a second portion of the air through apertures **46** in the nozzle **36** as indicated by direction **48b**. The nozzle **36** can include hinge connections **37** so that the nozzle **36** and, hence, the speed of the exhaust gases therethrough, can be adjusted during operation. The nozzle **36** is also cooled by a flow of cool air provided from the turbocooler **100** through an inlet **102** of the fan duct **32** at an axial location proximate to the augmentor **38**. The cool air from the turbocooler **100** mixes with the air in the fan duct **32** and flows through the apertures **48b** in the nozzle **36** to cool the exhaust nozzle or other hot engine components. By reducing the temperature of the nozzle **36**, the cool air from the turbocooler **100** can reduce the infrared signature of the aircraft.

[0029] The turbocooler **100**, which can be a conventional device, includes a turbine **104** and a compressor **106** connected by a rotatable shaft **108**. The shaft **108** is configured to be rotated, e.g., by the expansion of gas flowing through the turbine

104. As shown in Figure 2, the compressor **106** of the turbocooler **100** is fluidly connected by line **112** to the precooler heat exchanger **90** to receive a flow of pressurized bleed air from the compressor **20** of the engine **10**, which can be cooled in the precooler heat exchanger **90** before flowing to the compressor **106**. The bleed air is then further compressed in the compressor **106** of the turbocooler **100** and discharged to the fuel/air heat exchanger **110** through line **114**. The fuel/air heat exchanger **110** also receives a flow of the fuel from the fuel source **70**, e.g., through the control unit **72**. The fuel/air heat exchanger **110** transfers thermal energy from the bleed air to the fuel, thereby cooling the bleed air. The air then flows from the fuel/air heat exchanger **110** through line **116** to the turbine **104** of the turbocooler **100**, where the air is expanded and further cooled. Thereafter, the cool air from the turbocooler **100** is delivered through line **118** to the fan duct **32** for cooling the exhaust gas as described above. Cool air from the turbocooler **100** can also be delivered to other devices on the aircraft that require cooling or devices that further cool the air.

[0030] The fuel/air heat exchanger **110** can be a single heat exchanging device or multiple heat exchanging devices arranged in parallel or series arrangements. In either case, the fuel that flows through the heat exchanger **110** for cooling the bleed air is heated by the bleed air and thereafter can be provided directly to the engine for combustion or can be recirculated to the fuel source **70**, e.g., via the air/fuel heat exchanger **86** as described above.

[0031] Additional control devices such as valves and pumps can be provided for controlling the flow of the air and fuel to and from the various engine components. For example, valves **120**, **122** and/or pumps can be provided in the lines **112**, **114**, **116**, **118** connecting the turbocooler **100** to the precooler heat exchanger **90**, the fan duct **32**, and/or the fuel/air heat exchanger **110**. The flow of the fuel can be controlled by the control unit **72** and/or by additional control devices. Thus, the flow rate of each of the fluids can be adjusted by a controller, e.g., to achieve a desired rate of thermal cooling, desired rates of fuel flow to the combustor **26** and augmentor **38**, a desired rate of air flow to the fan duct **32**, desired maximum or minimum temperatures of the fuel and air, and the like.

[0032] It is also appreciated that the fuel can be circulated to other components of the engine **10** to cool the engine components and/or the exhaust air discharged from the engine **10**. For example, as shown in Figure 3, the augmentor **38** defines a fluid circuit **130** extending between an inlet **132** and outlet **134** and is configured to

circulate fuel therethrough. Fuel supply line **136** delivers fuel to the augmentor **38** via line **138** for discharge into the central passage **30** and combustion therein in an afterburner mode of operation. In another mode of operation, e.g., when the engine **10** is not operating in the afterburner mode and valve **140** is closed so that the line **138** is not delivering fuel to the augmentor **38**, valve **142** can be opened so that fuel is supplied via line **144** to the augmentor **38** for circulation through the fluid circuit **130** between the inlet **132** and outlet **134**. The fuel circulated though the fluid circuit **130** of the augmentor **38** cools the augmentor **38**. Since the components located at and aft of the augmentor **38** have a significant influence on the infrared signature of the aircraft, cooling these hot engine components can result in reduced signature benefits. Fuel cooling of the augmentor **38** can also improve the durability of augmentor components. Thereafter, the heated fuel is delivered from the augmentor **38** through the outlet **134**. The outlet **134** is fluidly connected by line **146** to the combustor, e.g., selectively via the precooler heat exchanger **90** or a bypass line **148** that bypasses the precooler heat exchanger **90**. A portion of the fuel can also be recirculated to the flow control unit **72** and/or the fuel source **90** via return line **150** and valve **151**.

[0033] As described above in connection with the embodiments illustrated in Figures 1 and 2, control devices such as valves and pumps can be provide for controlling the flow of fluids through the engine **10**. For example, in addition to the valves **94**, **140**, **142**, a valve **152** can be provided for controlling the flow of fuel from the control unit **72** to the precooler heat exchanger **90**, and check valves **154**, **156** can be provided for controlling the direction of the flow of the fuel from the augmentor **38** to the combustor **26**.

[0034] Each of the heat exchangers described above, such as the fan duct heat exchanger **60**, can be a variety of heat exchanging devices. For example, Figure 4 illustrates a portion of a core section of a heat exchanger **160** that can be used in any of the embodiments of the present invention. The heat exchanger **160** typically includes a first set of fluid passages **162** for circulating the fuel and a second set of passages **164** through which air flows. The fluid and the air can flow in the same or different directions **166**, **168**. In either case, the passages **162**, **164** are generally fluidly disconnected but thermally communicate so that thermal energy from the air is transferred to the relatively cooler fuel. Thus, the air is cooled and the fuel is heated during passage through the heat exchanger **160**.

[0035] In addition, the heat exchangers used in the present invention can include a device for transducing some of the thermal energy of the fluids into electricity. For example, as illustrated in Figure 4, an electron tunneling device **170** can be disposed between the adjacent passages **162**, **164** so that thermal energy transferred between the passages **162**, **164** results in a heat flux through the electron tunneling device **170**. The electron tunneling device **170** is configured to convert a portion of the heat energy to electricity. For example, as schematically illustrated in Figure 5, the electron tunneling device **170** includes a silicon wafer **172** and a titanium microlayer **174** on one side of the silicon wafer **172**. The titanium microlayer **174** is directed toward a silver microlayer **176** on a copper substrate **178**, but the titanium and silver layers **174**, **176** are separated by a small gap **180**, e.g., a gap having a dimension **D** of between about 10 and 40 angstroms. The electron tunneling device **170** can be encased in an oxide seal layer **186**. The silicon wafer **172** and copper substrate **178** function as a cathode and anode, respectively. The electron tunneling device **170** is disposed in the heat exchanger **160** with the silicon wafer **172** proximate to one of the air passages **164** and with the copper substrate **178** proximate to one of the fuel passages **162**. Thus, as the fuel and air pass through the passages **162**, **164** thermal energy is transferred in a direction **182** across the gap **180**, thereby causing an electrical potential to occur between the silicon wafer **172** and the copper substrate **178**. Thus, the silicon wafer **172** and copper substrate **178** can be electrically connected to an electrical device **184**, such as a battery or other electrical storage component, so that some of the thermal energy of the air is converted to electrical energy instead of heating the fuel.

[0036] In some embodiments of the invention, the electron tunneling device **170** can be in thermal communication with the nozzle **36** or other components of the engine **10**. For example, the cathode side of the electron tunneling device **160** can be placed in contact with the nozzle **36**, and the anode side of the device **160** can communicate with one of the fuel passages **162** so that the nozzle **36** is cooled, with a portion of the thermal energy from the nozzle **36** heating the fuel and a portion of the thermal energy being converted to electricity by the electron tunneling device **160**. Further, it is appreciated that transducing devices other than the electron tunneling device **160** can be used in the present invention. For example, a thermoelectric generator can be used to generate electricity as a voltage is established in a conducting material that is subjected to a temperature gradient, i.e., the Seebeck effect.

Transducing devices and methods of making such devices are further described in U.S. Patent No. 6,100,463 to Ladd, et al., titled "Method for Making Advanced Thermoelectric Devices," the entire content of which is incorporated herein by reference.

[0037] Many modifications and other embodiments of the invention set forth herein will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.